Cassini Science Planning Process

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1. Abstract

The mission design for Cassini-Huygens calls for a four-year orbital survey of the Saturnian system and the descent into Titan's atmosphere and eventual soft-landing of the Huygens probe. The Cassini orbiter tour consists of 76 orbits around Saturn with 44 close Titan flybys and 8 targeted icy satellite flybys. The Cassini orbiter spacecraft carries twelve scientific instruments that will perform a wide range of observations on a multitude of designated targets. The science opportunities, frequency of encounters, the length of the Tour, and the use of distributed operations pose significant challenges for developing the science plan for the orbiter mission. The Cassini Science Planning Process is the process used to develop and integrate the science and engineering plan that incorporates an acceptable level of science required to meet the primary mission objectives for the orbiter. The bulk of the integrated science and engineering plan will be developed prior to Saturn Orbit Insertion (SOI). The Science Planning Process consists of three elements: 1) the creation of the Tour Atlas, which identifies the science opportunities in the tour, 2) the development of the Science Operations Plan (SOP), which is the conflict-free timeline of all science observations and engineering activities, a constraint-checked spacecraft pointing profile, and data volume allocations to the science instruments, and 3) an Aftermarket and SOP Update process, which is used to update the SOP while in tour with the latest information on spacecraft performance, science opportunities, and ephemerides. This paper will discuss the various elements of the Science Planning Process used on the Cassini Mission to integrate, implement, and adapt the science and engineering activity plans for Tour.

2. Mission Overview

Launched from Kennedy Space Center on Oct. 15, 1997, the Cassini-Huygens spacecraft will reach the Saturnian region in July 2004. After a seven-year voyage that includes four gravity-assist maneuvers, Cassini will enter Saturn's domain and begin a four-year mission that includes more than 70 orbits around the ringed planet and its moons and deploy the Huygens probe into Titan's atmosphere. The main scientific goals include measuring Saturn's huge magnetosphere, analyzing, from up close, the stunning ring system, studying Saturn's composition and atmosphere, as well as detailed, targeted observation campaign's of Titan and the other large satellites. Once the spacecraft's onboard recording device (2 solid state recorders holding 2Gbits each) reaches capacity, it will point its high-gain antenna toward Earth and download the data through one of the antennas of the Deep Space Network. Cassini will be sending home, on average, over one gigabyte of data daily. The data will then be analyzed by more than 200 scientists worldwide.

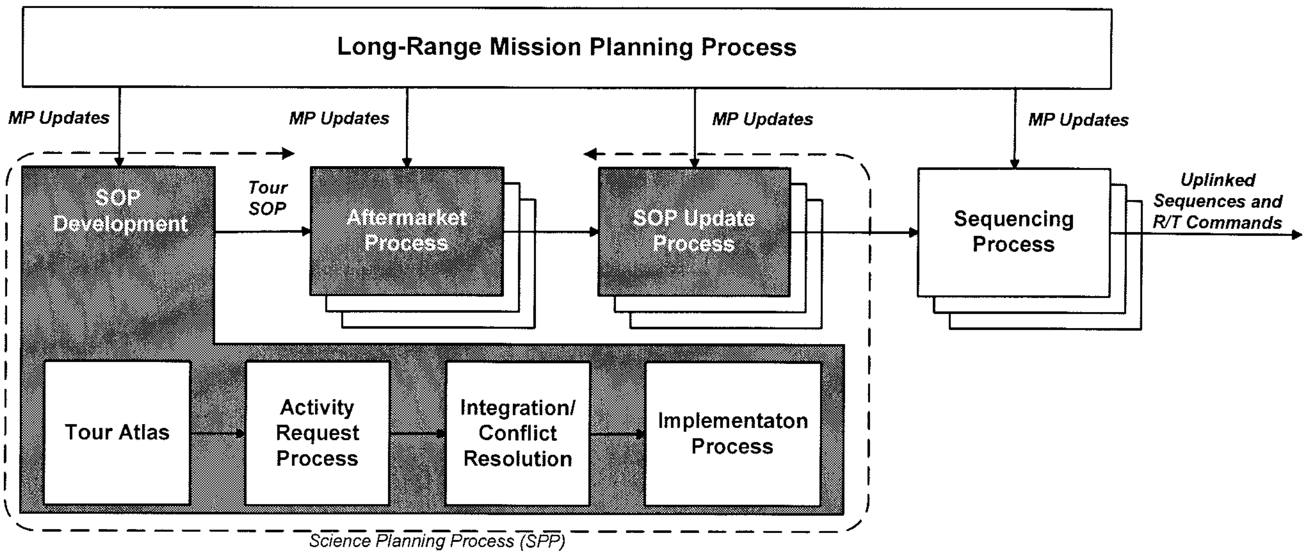
Cassini is a three-axis stabilized spacecraft outfitted with 12 diverse science investigations. The instruments often have multiple functions, equipped to thoroughly investigate all the important elements that the Saturn system may uncover. The spacecraft communicates through one high-gain and two-low gain antennas. Power is provided by three Radioisotope Thermoelectric Generators -- commonly referred to as RTGs. Finally, Reaction Wheel Assemblies (RWAs) are one of the two systems used to provide pointing control of the spacecraft in flight (with the thrusters of the Propulsion Module Subsystem as the other). The reaction wheel assemblies contain electrically powered wheels that move and hold the spacecraft very steadily.

3. Cassini Science Planning Process

The Cassini Science Planning Process is the process used to develop the science and engineering plan that incorporates an acceptable level of science required to meet the primary mission objectives for the orbiter. Prior to Science Planning the Mission Planning Team leads an effort to design the tour. This effort is focused on maximizing the science opportunities of the mission and is somewhat independent of the detailed spacecraft design. It is during the Mission Planning phase where decisions are made regarding how many orbits, how many Titan flyby's, which icy satellites will be targeted - how often and at what orientation. The tour design for Cassini took over 6 years. The science community plays an integral role in this process. The Science Planning Process (see Figure 1) follows tour design and consists of three elements:

1. Creation of the Tour Atlas, which identifies the specific science opportunities in the selected tour. All stellar and solar occultation's are tabulated for both atmospheres and rings targets. The detailed information (phase, altitude, surface ground track, etc.) for each targeted flyby is provided, etc. The

Figure 1. **Cassini Science Planning Process Flow**



creation of the tour atlas has been ongoing for several years and continual improvements are published.

2. Development of the Science Operations Plan (SOP) is broken down into two major phases: Integration and Implementation. Integration is the process by which the science and engineering teams negotiate the basic pointing, power, and data management strategy given the science opportunities present, the constraints placed on the spacecraft from various subsystems (i.e. reality), and the relative scientific return of any observation or set of observations. Implementation is the process by which these plans are validated. Integration took over 3 years and Implementation will take about 2.5 years.
3. The Aftermarket and SOP Update uplink processes are used to update the SOP while in tour with the latest information on spacecraft performance, science opportunities, and ephemeredes. The Aftermarket process is where the Science Instrument Teams have the opportunity to make minor adjustments to the integrated plan. The SOP Update process is where this updated plan is re-implemented and re-validated prior to the final sequence process and radiation to the spacecraft. Aftermarket and SOP Update will take 4 years.

The selection of the Cassini Science Planning Process, and in particular deciding on the best approach for integrating the Tour, was in itself a challenge. The distributed operations nature of the Project required the general overall buy-in of the process by the Project Science Group. The basic work in integration is negotiating the best possible science plan given the constraints of the spacecraft and tour. This required significant support from the science members on the Instrument Teams. Three options were considered for integrating the Tour:

1. Use a very small, very science-savvy group co-located at JPL to integrate the Tour. This small group would essentially be put into a room and negotiate the Tour with limited interaction with the Project Science Group. This team would be able to integrate the Tour very quickly, but the science plan would not have been optimized and many of the opportunities the science community fought for during the tour design would not make it into the plan. This also places a huge workload burden on a very small group, and the politics of empowerment would be a significant issue.
2. Use a very large single group consisting of the entire Project Science Group to integrate the Tour. Essentially put everyone into a very large room and start negotiating, sharing the workload amongst the entire science community. This solves the empowerment problem, but it slows down the process considerably as the dynamics of large groups come into play. This was how we planned the Jupiter Encounter. However, the planning-to-execution ratio for Jupiter was too large to accomplish the integration of the Tour in time.
3. Use multiple discipline-focused science groups to share the responsibly and the workload of integrating the Tour. This was the approach we ultimately adopted to integrate the Cassini Tour. The smaller science discipline-focused groups were Rings, Atmospheres, Icy Satellites, Titan,

Magnetosphere, and Cross-Discipline. Integrating the Tour based on these science discipline-focused groups leads to a more science-optimized plan. The benefit of using this approach is that you have 6 parallel efforts and the workload is distributed accordingly, but of course, it's all in parallel. Co-leadership of these groups was shared between the Cassini Science Planning Team and a member of the Project Science Group, which dealt with the empowerment issue. The disadvantages of this approach are that you have parallel efforts and some science teams needed to be represented in all of these groups. For a few of the science teams this would be a burden. Also, lessons learned in one group were not necessarily learned in the other groups. However, this approach seemed to provide the best balance of resource utilization and meeting the schedule drivers on the Project.

For Implementation, Cassini inherited much of its approach from the Galileo Science Planning effort. The lessons learned for Galileo and the unique Cassini challenges were factored into the implementation process. This process was first exercised during the Cassini Jupiter Encounter and refined throughout cruise for Tour use. The process has matured significantly over the past several years since Jupiter.

The details of Integration and Implementation are critical to the overall process of Cassini Science Planning. During Integration Cassini Science Planning led six simultaneous teams consisting of scientists from around the world, science operations personnel from JPL and around the world, SP engineers at JPL, and spacecraft team members at JPL. The four-year tour was subdivided into roughly 200 smaller time segments based on science discipline – Rings, Atmospheres, Titan, Icy Satellites, Magnetosphere, and finally Cross-Discipline (everything else). A typical orbit consists of a Cross-discipline segment through the long apoapsis period, then a targeted Titan or Icy Satellite flyby, and then the time around periapsis, which is usually integrated by the Rings or Atmospheres groups. Late in the mission when the inclinations are high and the orbits are short the Magnetosphere group replaces the Cross-Discipline group as the major integrator.

The output of Integration is a conflict-free timeline of all science observations and engineering activities stored in a centralized database. These activities have associated data volumes that are consistent with the downlink strategy (also incorporated into the timeline), and associated power and thermal requirements that are consistent with a predefined set of operational modes. The integrated plan also identifies the instruments responsible for controlling the attitude of the spacecraft as a function of time (i.e., a conflict-free pointing profile).

The conflict-free pointing profile merits special mention. Cassini devised a system of sharing the responsibility of pointing the spacecraft among the distributed science teams. During Integration, the Science Planning Team spends a significant amount of time coordinating which instrument will point the spacecraft where, and when, and for exactly how long. The general strategy is to have a "waypoint". Waypoints are a series of basic attitudes that are safe, and stay safe for quite some time. Each instrument picks the spacecraft up at the current waypoint, does their observation and then returns to the waypoint. In this way, every instrument is independent of the pointing on either side of them. The waypoint changes from time to time as observation campaigns complete or a waypoint becomes unsafe.

During Implementation, the Science Instrument Teams, Science Planning, Optical Navigation, and the Engineering Team generate the detailed spacecraft pointing and data acquisition commands necessary to accomplish the integrated science plan. These command files are validated using the Cassini Ground Software system to ensure that the plan will execute on the spacecraft without violating any flight rules and constraints. An end-to-end pointing profile validation is conducted during Implementation. Cassini Science Planning laid out schedule where, sequence-by-sequence, the basic pointing designs were collected from the distributed sites, combined with the commands to control the data volume and power and merged into a single sequence. All teams, in particular the spacecraft team, validate this merged sequence. All problems and a second and final validation cycle is used to refine the sequence prior to placing it on the shelf for later use. The SOP (Integration and Implementation) is complete when the final sequence is validated in January of 2005.

It's worth noting that originally there was a plan to simplify operations for the Cassini mission. The mission was designed to be an intense four-year tour, with abundant science opportunities but with a limited budget. It was felt that without simplifying operations we wouldn't succeed. First, there would be a limited number of power envelopes, called operational modes. These op-modes would be validated, the transitions to and from them would be validated, and then once the spacecraft was placed in a known op-mode a complete power and thermal check was not needed. Only 2% of the mission would be in a unique power configuration and require a full power and thermal validation. Second, the teams were to create and use reusable sequence constructs. Once a single "system scan" had been designed and validated it would be used over and over. Of those original simplifying constructs, only the power envelope simplification came to fruition. Cassini has developed about 15 op-modes, which have validated transition sequences built, and less than 2% of the mission uses a unique configuration, which requires rigorous validation. The significant use of reusable sequence blocks could never be incorporated into the integrated plan. Implementation becomes a pointing and data volume validation process as we use op-modes for the majority of tour.

The overall timeline of events associated with the Cassini uplink development process is given in Figure 2. This chart maps out the timeframe for the key steps in the uplink process, the key players, and the goal of each step. It covers the time period from Tour Design to the sequencing process that occurs just prior to radiation of the sequence command load to the spacecraft.

Figure 2. **Cassini Uplink Development Timeline**

When	What (goals)	Who	Details
10 years before Prime Mission	**Tour Design** (maximize science opportunity)	Science Community, Mission Planning (some Spacecraft)	Science experiment trade-offs, navigation and uplink development capabilities.
4 years before PM	**Integration** (negotiate best science compromise)	Science Planning, Science Community (some Spacecraft, some Mission Planning)	Break up entire mission by science discipline and negotiate shared resources (pointing, power, telemetry, and data volume); lack of a scan platform makes this a challenge.
2 years before PM	**Implementation** (validate basic sequence design)	Science Planning, Science Operations, Spacecraft Team (some Mission Planning)	2 validation cycles to get a 'flyable' skeleton sequence of the shared resources in place; distributed operations makes this a challenge.
20 weeks before execution	**Aftermarket (Adaptation)** (update integrated plan)	Science Planning, Science Community (some Spacecraft, some Mission Planning)	Update integrated plan based on new discoveries, science data analysis, spacecraft/instrument performance changes, etc.
15 weeks before execution	**SOP Update (Implementation Update)** (update basic sequence design)	Science Planning, Science Operations, Spacecraft Team, (some Mission Planning)	A validation cycle to update the skeleton sequence to any updated science compromises and/or new discoveries.
10 weeks before execution	**Sequencing** (validate entire sequence)	Sequence Lead, Science Operations, Spacecraft Team (some Science Planning)	2 validation cycles to create a complete sequence with all commands in place; complexity of spacecraft and plans make this a challenge.

4. Cassini Science Planning Challenges

The Cassini Science Planning effort had to overcome many challenges. The first and foremost of these was the lack of a scan platform. With all the instruments being body mounted onto the spacecraft, if you want to point any particular instrument at any particular target the entire spacecraft has to move. Almost all pointing desires are mutually exclusive which results in a time-sharing of the spacecraft. Roughly 15 hours of observations (instruments pointed at targets of interest) are accomplished each day, and 9 hours of downlink (High Gain Antenna pointed to Earth).

The second major challenge for Cassini was distributed operations. Initially, the thought was that distributed operations was an efficient way to do business and a major cost saver. Distributed operations is very effective if you have a match between spacecraft design and the operations environment. The team in charge of achieving the science goals, is the same team who builds the instrument, is the same team who commands the instrument, is the same team who monitors the health and safety of the instrument, is the same team who respond to anomalies, etc. Unfortunately Cassini also choose to distribute the basic pointing of the spacecraft with all the attendant risks. Distributing out the basic pointing of the spacecraft in retrospect did not achieve the desired goal of simplified, lower cost operations. Certainly there has been no cost savings and the infrastructure we developed to support this concept was significant.

Next, to achieve the competition of the SOP by January 2005 required a large number of simultaneous/concurrent processes. The ratio between planning and operations for Cassini is one of the smallest for a mission of this kind (see Figure 3). Voyager and Galileo were spacecraft that had a similar complement of instruments going into a similar environment (outer solar system, requiring long round trip light-times), with many of the same science goals. Voyager was a flyby mission and essentially had long

Figure 3. **Mission Comparison**

	CHARACTERISTIC	VOYAGER	GALILEO	CASSINI
MISSION	Orbits	6 (flybys)	11	75
	Average Orbit Duration	120 days (flyby)	8 weeks (5 wks - 8 wks)	3 weeks (1 wk - 3months)
	Operations Environment	Centralized	Centralized	Distributed
	Prime Mission Duration	2 years	2 years	4 years
	Total Mission Data Volume	~4,000 Gbits	2 Gbits	~3,000 Gbits
SPACECRAFT	Scan Platform	Yes	Yes	No
	Maximum Turn/Slew Rates	1°/sec	1°/sec	0.4°/sec-RCS 0.2°/sec-RW
	Power Modes	1	8	12
	Recorder Volume	.5 Gbits	.9 Gbits	4 Gbits
	Imaging Instruments	2	2	8
	Science Instruments	11	12 Orbiter 6 Probe	12 Orbiter 6 Probe
UPLINK PLANNING	Science Plan Development Time	9:1	5:1	3:1
	Sequence Loads/Orbit (Average)	10 loads/flyby	3 (1 encounter, 2 orbital cruise)	4-5 weeks (n orbits/load)
	Targets & Periapses/Load (Average)	10 loads/flyby	1periapse, 1satellite	2 periapse, 2 satellites
	Sequence Load Size	2.5 Kwords	16 Kwords	150 Kwords
	Science Operations Staff (JPL)	~60	60	23
	Investigation Team Size	~150	187	254

planning stages for relatively short intense flybys – planning-to-execution ratio was 9-to-1. Galileo was an orbiter but had large orbits, so essentially long relaxed portions of the tour and then short bursts of intense activity – planning-to-execution ratio was 5-to-1. Cassini, starts with a few large orbits but then settles down fairly quickly to small orbits with intense bursts of activities happening every 2 weeks or so and our planning-to-execution ratio is 3-to-1. The sequences are approximately 4 to 5 weeks and the scheduled planning process stretches out roughly 20 weeks ahead of each sequence.

The fourth challenge was the development and delivery of needed software after integration and implementation work had begun. There are many pointing constraints for this spacecraft that come from the instruments and spacecraft subsystems. For example, the Optical Remote Sensing instruments have restrictions regarding pointing the boresights (narrow, tight cones of avoidance) towards the Sun, they also have restrictions regarding pointing the radiators (which are 90 degrees away from the boresight, but encompass a full 180 degrees) towards the sun. These constraints eliminate large portions of available targets, e.g. whole hemispheres are excluded. There are a variety of constraints placed on the distributed teams, and yet they have to develop and deliver commands that achieve their science goals, but keep the entire spacecraft safe. The Cassini Mission developed software to easily allow a distributed site to point the spacecraft. This was a major endeavor. We had a team of programmers working at JPL to produce software that was sufficiently functional to do every kind of pointing that all the science teams would like to do with ease, but also robust enough to check all the flight rules and constraints that had to be checked, and was portable enough to be used around the world on various platforms, and that was available early enough that it could be used in the planning stages.

We needed the capacity to validate the basic pointing desires early in the planning stages and the software was not ready. The software was working towards the implementation deadline, where it could do the complex job of creating the entire pointing command sequence, check the entire set of constraints, and interface with the spacecraft attitude system, etc. The Integration effort, which preceded the Implementation effort, was challenged to understand these pointing constraints. We started down the path of doing all this planning and found that we had to go back and retrofit our plans based on pointing constraints we had not understood until we implemented the first set of sequences. The timeliness of constraints and the timeliness of the software being developed became a tremendous challenge for science planning. They were not ready early enough, and resulted in rework. The pre-/post-launch funding profile was the primary reason for the late development of the Cassini ground software system and tools.

Next, the tour was not selected in a timely way. The development of the SOP could not begin until the final tour was selected. The Project Science Group spent several years working with the Tour Designers to come up with the best overall tour. A number of tweaks were proposed to the baseline tour that delayed the final decision of the tour. The development of the Tour Atlas and the subsequence Integration and Implementation activities could not proceed until this critical decision was made. As a result, the late decision delayed the start of SOP development.

And finally, the available funding resources factored into the schedule and scope of the integrated and implemented plan. As funding became an issue the science plan was descoped accordingly to accommodate the available staffing resources.

5. Cassini Science Planning Current Status

As of January 2004 we have completed the integration of the entire Cassini Tour. Implementation of the SOP is proceeding smoothly with more than 60% of the Tour complete. We have also completed the re-integration process, i.e., Aftermarket process, for the first 3 Tour sequences, and have re-implemented these sequences in preparation for final uplink to the spacecraft. The first Tour sequence begins execution on the spacecraft on May 14, 2004. We complete the SOP implementation for the remainder of the Tour in January 2005.

6. Lessons Learned

To wrap up, there are 5 major lessons learned from Cassini Science Planning.

1. Consideration of operability should be factored into spacecraft development. The lack of a scan platform significantly increased the workload required to develop the SOP. The operations cost associated with integrating and implementing the science plan without the scan platform outweighed the costs saved pre-launch from the removal of the scan platform. Mission Operations & Data Analysis (MO & DA) costs should be taken into consideration during these types of pre-launch development trades.
2. Distributed operations is not a low cost operations option. It works very well in certain situations, but it's doesn't lower the overall cost of the mission. The development of redundant hardware and software infrastructures both at JPL and the distributed sites is a result of distributed operations. Ground software development, as necessary, at the distributed sites rarely leads to that tool being used or useful to the other teams. Also, the Cassini Project would have benefited from centralizing the pointing of the spacecraft to JPL with a small targeted, entirely trained team that interfaced with all the science teams to achieve the pointing goals of the teams.
3. Exercising the systems as early a possible with real in-flight activities. Utilizing the ground and flight systems lead to useful lessons learned that could be applied to the prime mission. The Jupiter flyby, even though it was a distant, slow encounter brought all the science teams, spacecraft subsystems and navigation team working early to understand the constraints of the ground and flight systems.
4. Effective communication. Some tools used by Cassini to improve the lines of communication to the distributed sites included: a) e-mail distribution lists, which the distributed sites can sign up

for remotely, b) multiple teleconferences lines for group meetings, and most importantly, c) a central website as a source of latest information on the status of the integrated and/or implemented sequences.

5. Centralized web-based database. All the distributed sites went to single, central database to put in their observational requests. This resulted in everyone having access to the most current and up-to-date versions of those requests. All teams were working from the same database to extract the current state of the science plan. With 6 parallel integration efforts and simultaneous implementation efforts, a centralized database that is the one true source of information that the distributed sites can access all over the world is critical.